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Recent studies have shown that the traditional practice of monitoring outdoor (ambient) air quality leads to little information regarding the exposures of people in indoor surroundings. Consequently, EPA has begun a series of studies to determine the air pollution exposures people are subjected to in their daily non-outdoor activities at home, in traffic, and at work. This paper describes the factors that should be considered in developing a survey to describe the air pollution exposures that people experience in their home environment.

There is little previous experience in survey design for indoor air pollution exposure per se. However, the field of survey design for measurement of people's attitudes, preferences, and attributes is well developed. An extensive literature exists which describes general sampling techniques for performing these surveys. Some types of surveys, such as health care surveys or business surveys, are best addressed by particular types of survey designs. For example, the design issues for health care surveys are discussed in detail by Cox and Cohen.

This paper discusses the design considerations that make indoor air exposure surveys, where human subjects are recruited either to carry personal monitors or to allow monitoring in their homes, different from the traditional surveys of opinions and attitudes.

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Sample Design Considerations for Indoor Air Exposure Surveys

INTRODUCTION

Recent studies have shown that the traditional practice of monitoring outdoor (ambient) air quality leads to little information regarding the exposures of people in indoor surroundings.[1,2] Consequently, EPA has begun a series of studies to determine the air pollution exposures people are subjected to in their daily non-outdoor activities at home, in traffic, and at work.[3] This paper describes the factors that should be considered in developing a survey to describe the air pollution exposures that people experience in their home environment.

There is little previous experience in survey design for indoor air pollution exposure per se. However, the field of survey design for measurement of people's attitudes, preferences, and attributes is well developed. An extensive literature exists which describes general sampling techniques for performing these surveys.[4] Some types of surveys, such as health care surveys or business surveys, are best addressed by particular types of survey designs. For example, the design issues for health care surveys are discussed in detail by Cox and Cohen.[5]

This paper discusses the design considerations that make indoor air exposure surveys, where human subjects are recruited either to carry personal monitors or to allow monitoring in their homes, different from the traditional surveys of opinions and attitudes.

DIRECT VS. INDIRECT MEASUREMENT APPROACHES

A person's exposure to an air pollutant at a particular point in time is defined by the concentration of that pollutant in the air that he or she inhales. In a dwelling in which no one is at home, the concentrations of air pollutants in the dwelling do not represent an exposure because no one is exposed. Only when a person enters that home and breathes the air do the concentrations result in an indoor exposure. This distinction is important to remember when considering the two approaches, direct and indirect, used by EPA to determine indoor air exposures.

In the direct approach, a subject carries a personal exposure monitor (PEM) that measures the pollutant concentrations in the air the subject breathes while indoors. This technique has been used successfully to measure indoor exposures to CO.[6] When the subject enters and leaves an indoor setting, a button is pushed that initiates and completes the time integral of concentration to produce an average exposure for that interval.

The indirect approach utilizes measures of the subject's indoor activities and locations to ascribe to each time period an estimated concentration typical of the subject's setting and activity. For the indirect approach to be reliable, accurate concentration estimates and validated models must be available.

A potential difference in the exposure estimates obtained under the two approaches arises from the fact that the concentration of a pollutant in a

home when no one is present may be different from the concentration in the home when people are there. For instance, a measured 24-hour mean concentration of a cigarette smoke constituent in a home can represent an average over three conditions: 1) no one at home, 2) someone home but no one smoking; and 3) someone smoking at home. If the indirect approach uses the 24-hour average concentration to represent the exposure of a person who visits that home for one hour, an error will be generated by the effect of pooling all three conditions into one estimate. Because indoor concentrations of combustion products are usually higher when people are present (sources like cigarettes and kerosene heaters are generally not operating when people are not home), an integrated average concentration over all three conditions will generally be lower than the exposure actually experienced. This problem could be alleviated by placing a PEM on the subject, rather than using a stationary monitor in the home. However, the use of PEMs has important cost and respondent burden implications. These factors make it important that the survey designer carefully consider the differences between direct and indirect exposure estimation.

DETERMINATION OF THE INDOOR AIR QUALITY (IAQ) SURVEY OBJECTIVES

The first step in the design of an IAQ survey is to develop a detailed list of survey objectives. These objectives will motivate the entire sample design. The population to be sampled and the data to be collected are directly dependent upon the survey objectives. By clearly specifying the survey objectives in advance, the researcher is protected against the embarrassing situation of having inadequate precision for survey estimates or of being incapable of responding to important questions about the indoor air environment.

In developing the survey objectives, the planner should formulate as complete a list as possible. The objectives should focus on the uses to which the data are to be put and the questions that the data must answer.

The initial set of objectives are usually general statements of survey intent that must subsequently be specified in greater detail to develop the sample design and data collection plan. For instance, precision requirements for survey estimates must be formulated and cost constraints determined. Consideration must also be given to the type of measurement methodologies that are available, and their associated respondent burdens. The planner must recognize that in spite of the apparent economies of scale in a larger survey, increasing the number of survey objectives a survey generally increases the cost to the sponsor and the burden to the subjects. Thus, it may be more cost effective to address separate objectives in separate studies than to attempt to meet them all at once. For example, the objectives of determining the national distribution of indoor concentrations of benezene and the health effects of benzene exposure may require the use of different surveys and populations, such as a random sample of housing units (HUs) for the first and a sample of human subjects for the second.

In theory, the survey design that meets the stated objectives for the minimal cost is the desired product. In practice, the budget available for the project is usually less than the minimum amount required to meet the objectives and compromises have to be made. This process of modifying the survey design to meet the cost constraints balances the reduction in precision

of the estimates due to the use of a smaller sample against maintaining the sample size but deleting an objective from the study.

DEFINITION OF THE TARGET POPULATION

The target population for a survey is the entire set of elements about which the survey data are to be used to make inferences. For IAQ surveys, the target population is usually composed of persons or residential housing units. The definition of the target population for a particular survey follows directly from the survey objectives.

As an example, the target population for the Nonoccupational Pesticide Exposure Study (NOPES) will be the civilian noninstitutionalized adult residents of Jacksonville, Florida.[7] Populations on military bases and in institutions were excluded because pesticide applications in their residential areas may not be under the control of the subjects themselves. The target population was limited to adults because of the requirement to carry a PEM and because adults are more likely to be the class of subjects applying the pesticides in the home environs. In a study of the potential for high CO exposures in a community, commuters were chosen as a target population because of their high expected traffic contributions.[8] In the proposed National IAQ Survey (NIAQS) for organic pollutants, the target population consists of all HUs that constitute the permanent residence of the occupant. The target population was defined in terms of HUs, rather than people, because the desired objectives of directly measuring personal indoor exposures cannot be met given the available resources and methodologies. The target population was limited to permanent residences because of the need for the HU concentrations to represent a potential for long term exposures to the individuals.

USE OF PROBABILITY SAMPLING

Probability sampling refers to sampling in which a list or mechanism (i.e., the sampling frame) is developed for enumerating the target population, and in which every unit on the frame has a nonzero probability of being selected for inclusion in the survey. Rosander[9] lists the following ten advantages possessed by a probability sample that is properly designed and implemented:

1. It provides a quantitative measure of the extent of variation due to random effects.

2. It provides data of known statistical quality.

3. It provides data in a timely fashion.

4. It provides acceptable quality data at minimum cost.

5. It has a built-in method of estimation.

6. It forces a sharper analysis of the problem and a clearer definition of terms.

7. It forces better control over nonsampling sources of error, that is, over bias.

8. Mathematical statistics and probability can be applied to analyze and interpret data.

9. It can yield better quality data than a census or 100% tabulation.

10. It provides within itself a basis for progressive improvement.

To summarize, the primary advantage of probability sampling is that a defensible basis exists for inference from the sample to the target population.

In regards to a national IAQ survey, probability sampling is unquestionably superior to subjective targeted sampling in which personal judgements are made by IAQ survey planners or field interviewers as to which population elements are to be included in the survey. Even when attempts are made to judgementally select "representative" units or to select units from all parts of the sampling frame, the subjective sample does not possess the advantageous properties of a probability sample. Hence, the survey results cannot be used to make defensible statistical inferences about target population.

CONSTRUCTION OF THE SAMPLING FRAME

The sampling frame for a survey is the list or mechanism used to enumerate population elements for sample selection purposes. The ideal frame is an actual list of population elements in which every element is listed once and only once and in which every listing represents an element of the target population. This ideal frame contains unique identifying information, address or location information, and auxiliary information about each element. As an example, the ideal frame for a national survey of permanent residential HU's would be a list of every home in the United States with name, address, and characteristics that relate to research questions, such as type of heating sources and amount of insulation. No HU would be listed more than once and further, each entry would correspond to a permanently occupied residence. Houses that were vacant or temporary residences would not be included on the list. The auxiliary information could be used for stratification to improve the precision of survey estimates. Of course, this ideal frame never exists for surveys of homes or persons, since complete, accurate lists are not available.

Frequently, a suitable list of target population members is unavailable, and it is cost prohibitive to create one for the entire population. In this situation, the target population can frequently be linked to geographic areas for which maps are available. A probability sample of these areas can then be selected.

SAMPLE SELECTION PROCEDURES

The typical national household survey has a complex design structure with several stages of sampling for which separate frames and different types of sampling procedures may be required. It is beyond the scope of this paper to

attempt to discuss these design types and sampling procedures in sufficient detail that the reader could implement them. Instead, design components that occur in most sampling plans will be reviewed. For additional information about the design of sample surveys, the reader should consult standard sampling textbooks such as Cochran[4], Kish,[10], or Sukhatme and Sukhatme.[11] The EPA guideline document for managing statistical surveys also provides useful information.[12]

Simple Random Sampling

The least complex sampling method is simple random sampling, which selects n units out of a population of N units in such a way that (1) no unit is selected more than once, and (2) each of the distinct samples has an equal chance of being selected.

Simple random sampling is not commonly used as the selection method for indoor air quality surveys for a number of reasons. Use of the method requires that a list of population elements be available, which is not the case for many populations. Even when lists are available, it may be more convenient to use a sequential selection method such as systematic sampling. The primary reason that simple random sampling is not commonly used is that it is often not cost effective. Techniques such as area sampling or stratified sampling frequently result in samples with lower costs or better precision. However, simple random sampling is commonly used as the benchmark for comparison of the efficiency of other sampling techniques.

Stratified Sampling

Frequently, the sampling frame contains ancillary information about the population elements that can be used directly in sample selection to increase the precision of survey estimates or to provide needed control over the distribution of the sample. Ancillary information that has been used in previous IAQ surveys includes geographic location, socioeconomic status, housing unit characteristics, and pesticide usage descriptors. The ancillary data may be used to partition the target population into groups, or strata. When sampling is implemented independently within these strata, the sample is said to be stratified. In constructing survey estimates, sample statistics are first computed for each stratum. Weighted combinations of these stratum statistics are then used to form the survey estimate of the population parameter and its associated variance. The weights are functions of the size of the stratum and the size of the entire population.

One reason for using stratified sampling is to increase the precision of survey estimates. The variance of survey estimates is reduced and hence the precision increased through stratified sampling when the strata are formed so as to maximize the between-stratum variation and minimize the within-stratum variation. Variables to use for stratification are those that result in homogeneity of the units within strata and heterogeneity between the stratum means.

For example, an NIAQS of combustion-produced organic contaminant concentrations could stratify HU's in the U.S. on smoking vs. nonsmoking, type of cooking "fuel" (all electric, natural gas, other), and use of supplemental heating "fuels" (electricity, gas, wood, kerosene, coal). The 30 combinations

(2 x 3 x 5) represent "cells" that could be randomly sampled in U.S. homes, and by knowledge of the weight of each cell, the mean concentration of combustion products in the U.S. and within each stratum could be estimated.

Another reason for using stratified sampling is to control the distribution of the sample. For example, stratifying by geographical areas, such as EPA regions, insures that the sample will be geographically dispersed. For an NIAQS where geographical differences may impose variations in climate variables and availability of sources of fuels for heating, it is desirable to stratify the nation into regions and then randomly sample from each region to assure that the sample covers the breadth of the nation and that a major area such as New England is not left out by chance. An NIAQS for radon could stratify the country by geological formations likely to contain uranium ore.[13]

A final reason to use stratified sampling is for operational convenience or necessity. When oversampling of population subgroups is required to meet survey objectives, it may be convenient to partition the population into comparable strata. A population subgroup is said to be oversampled when members of the subgroup are included in the sample at a higher rate than their occurrence in the population. Oversampling is typically used to increase the sample size for small subgroups that might otherwise have sample sizes too small to analyze.

For example, domestic coal burning for cooking and space heating is relatively rare in the U.S., except in some regions where the local supply and custom encourage its usage. Even if only 0.5% of the U.S. population uses coal, it still represents a possibly significant exposure category. Since a random sample of regional strata may not include any homes with coal stoves, it may be necessary to create a special strata and oversample it to obtain enough homes with coal stoves for meaningful analysis.

Area Samples and Clustering

Cluster sampling is a common feature of many sample designs because of the cost savings that can be obtained by clustering the sample. Multistage sampling procedures are typically used for area household samples.

The NIAQS sample design furnishes an example of area sampling procedures that are commonly used. The first stage of sampling in the design involves the construction of a first-stage sampling frame in which the entire land area of the United States is partitioned in primary sampling units (PSUs). These PSUs are defined in terms of counties or groups of counties. A first-stage sample of PSUs is then selected by stratified sampling where the strata are defined based upon regional differences. The sample PSUs are partitioned into second stage units (SSUs) which are defined in terms of Census-defined enumeration districts and block groups. Second-stage sample selections are then made from each sampled PSU. At this point, lists of dwelling units within the sample SSUs are developed. The next stage of sampling involves the selection of sample dwelling units from these SSUs. All eligible residences are included in the household survey.

Two advantages accrue from this area sampling approach. The first advantage is that list frames of target population members need to be developed for the sample areas only. No household survey could afford to

prepare such lists for the entire nation. A second advantage is that interviewing activity is also restricted to the sample areas, reducing travel time and cost. Even when list frames of target population members are available, geographical clustering of the sample can still be cost effective.

The disadvantage of cluster sampling is that the variance of a cluster sample is increased over the variance that would have been achieved had simple random sampling been used with the same sample size. The increased variance is the result of the tendency of physically clustered units to have homogeneous responses. In terms of indoor air quality, clustered residences such as apartments in the same building or homes in the same subdivision may have commonalities due to the following factors:

(1) Similar housing structures due to the same building plan or the same building codes being in effect during construction.

(2) Similar age of construction materials.

(3) Similar utilities such as natural gas for all such homes.

(4) Similar supplemental fuels due to local availability of wood or a local ordinance banning kerosene heaters.

(5) Similar socioeconomic status (income and education) among residents, which may lead to use of similar household products or similar hobbies.

(6) Similar ambient air quality, air temperatures, and wind speeds which influence the air exchange rate.

The within-cluster homogeneity is measured by the intracluster correlation coefficient, ρ, which is the correlation between units from the same cluster.

The cost effectiveness of a clustered design can be assessed by comparing its cost to that of a simple random sample with the same effective sample size. The effective sample size of a proposed design is the sample size required to achieve estimates of the same precision using simple random sampling. For clustered designs, the effective sample size is $n/[1+(b-1)\rho]$, where n is the total sample size, and b is the average cluster size. The cost advantage of clustered designs derives from the fact that the clustered sample of size n can often be obtained at less cost than a simple random sample of size $n/[1+(b-1)\rho]$.

A final consideration for clustered designs is the optimal number b of sample individuals to interview per cluster. To model this problem, consider a two-stage clustered design in which 'a' primary clusters are chosen from a total of A clusters. For each of the 'a' clusters that are selected, b homes are randomly chosen and a personal interview is conducted within each. The optimal value of these variables will depend upon the variance of the resulting estimators as well as cost factors. A model for the overall variable cost (C) when a clustered sampling plan is used is

$$C = n C_0 + a C_1,$$

where C_0 is the unit cost of an interview and C_1 is the variable cost per cluster. The unit cost C_0 will involve interviewer time, travel time within a cluster, and data processing costs. The per cluster component C_1 will primarily involve interviewer recruitment and training costs, travel time between clusters, and the field costs associated with finding and describing clusters. Using this cost model, the optimal number of interviews per cluster will be

$$Opt(b) = [C_1(1-\rho)/C_0\ \rho]^{1/2} \quad .$$

DETERMINATION OF THE TOTAL SAMPLE SIZE

A major design consideration for any survey is the determination of the sample size for the survey. The sample size will be a function of the analyses that are planned, the required precision of survey estimates, and the resources available for the survey. Most survey data analyses involve the computation of means, proportions, and cross tabulations and the comparison of estimates for population subgroups. By modeling the precision of these survey estimates, the sample size required to meet given precision constraints can be determined.

Examining the precision of survey estimates for the range of possible values of the parameter being estimated can provide an assessment of the sample size requirement. An approach that is frequently helpful is to calculate the coefficient of variation of the estimate, defined as the standard error of the estimate divided by the parameter being estimated. The survey objectives should be examined to determine the value that is required for the coefficient of variation of survey estimates. To use the coefficient of variation criterion, information is needed about the magnitude of the standard error. This information may be obtained from studies reported in the literature, by performing a pilot study, or by modeling the estimate and its standard error.

Many questionnaires are composed primarily of items with categorical responses, with continuous responses obtained for only a few items. In this situation, sample size requirements can be modeled by examining the precision of survey-estimated proportions. The variance of an estimated proportion can be expressed as a function of the parameter being estimated. The sampling variance of an estimated proportion, P, may be approximated by

$$Var(P) = [P(1-P)/n]DEFF,$$

where n is the sample size, P is the proportion being estimated, and DEFF is the design effect. The design effect for a survey estimate is defined to be the ratio of the variance of the statistic given the actual design divided by the variance that would have been obtained from a simple random sample of the same size. The design effect represents the cumulative effect of such design components as stratification, unequal weighting, and clustering, and will differ for each design. Past survey experience is usually the source of design effect estimates, as statistical literature provides little guidance.

This and other approaches can be implemented to determine the required sample size. The most important aspect of the sample size determination, however, is carefully examining the survey objectives to determine the types

of analysis that will be required, the reporting domains for the survey, and the required precision of survey estimates. If the sample size required to meet the survey objectives is not affordable given the resources available to the survey, some modification of the survey objectives, such as relaxation of the precision constraints, will be necessary.

RESPONSE RATE CONSIDERATIONS

All sample surveys experience some degree of nonresponse, which can occur at several levels. Total nonresponse occurs when the entire set of survey data is missing for a sample member, either because the sample member refuses to participate in the study, or because he or she cannot be found at home after repeated callbacks. When the survey involves multiple questionnaires or activities that respondents must complete, partial nonresponse occurs when a sample member initially responds but then fails to complete all of the questionnaires or required activities. Within otherwise completed questionnaires, certain question items may have missing responses due to refusal or insufficient knowledge on the respondent's part. This type of missing data, referred to as item nonresponse, will also occur when invalid data are discarded or when an item response is lost following collection.

If the values for most data items were distributed in a similar manner for respondents and nonrespondents, there would be no need to be concerned about the occurrence of nonresponse. In this situation, the available data could be analyzed directly and reliable estimates obtained for most types of survey statistics. However, the distribution of respondent data is often different from the nonrespondent distribution; hence, survey estimates obtained from respondent data will be biased with respect to describing characteristics of the survey population unless compensations are made for the missing data.

The potential for nonresponse bias in IAQ surveys is usually significant due to the magnitude of total nonresponse typically experienced in such surveys. Traditional household opinion or attitudinal surveys that use personal interviews for data collection generally have total response rates of 80 to 90 percent.[14] Response rates for IAQ studies are typically lower - in the 40-60 percent range for the TEAM studies.[15,16] The low response rates are typical of personal monitoring studies due to the unusually high level of burden imposed on the respondent.

Although the potential for nonresponse bias is high in IAQ surveys, the magnitude of the bias actually experienced has not yet been quantified. Some level of nonresponse bias is expected due to the correlation of response rate with factors thought to influence exposure, such as socioeconomic status and geographic location.

Survey design can play an important role in minimizing the impact of nonresponse, both by reducing the overall level of nonresponse, and by providing a basis for analytical treatment of the nonresponse that occurs. Good survey design will take into account the response characteristics of the target population, and may incorporate data collection techniques such as multiple callbacks, nonresponse followup subsampling, or monetary incentives, to increase response rates. Characteristics of the sample design can influence the way in which nonresponse is treated. For example, cluster sampling may make multiple callbacks an economically viable option for a

survey. If a particular subgroup of the target population is known to have low response rate, the sampling design may call for oversampling of that subgroup to ensure that an adequate number of completed responses are obtained for the subgroup.

A variety of analytical techniques, such as nonresponse weight adjustment and missing data imputation, have been developed for minimizing the impact of the realized nonresponse on the survey estimates. These techniques all depend on the use of probability sampling during sample selection.

CONCLUSIONS

Surveys will continue to play an essential role in the acquisition of information on exposure to indoor air pollutants. Application of established concepts of survey design when planning an indoor air quality survey will result in efficient use of available resources and collection of data with known statistical properties. Of particular importance is the need to use probability methods when selecting the sample. Some survey design methodologies, such as stratified sampling and the use of area frames, are particularly well suited to meet the objectives and data collection requirements typical of indoor air quality surveys. As more field experience is gained with these surveys, survey design will be able to be further refined, so as to provide greater precision at less cost.

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